Progress in Materials and Structures at Lewis Research Center

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The Lewis Research Center is NASA's focal point for the development of power and propulsion system technology. Aircraft gas turbine engines and rocket engines have traditionally received major attention. Because of this background, the Department of Energy has asked Lewis to assume an active role in the development of automotive gas turbine and Stirling engines as well as the technology for advanced electrical generation at both central utility stations and industrial cogeneration locations.

The development of successful power and propulsion systems requires the integration of many factors related to both improved materials and to design methodology. These systems require materials of high strength and high temperature capability which at the same time are lightweight, easily fabricated, and low cost. Moreover, for most applications those requirements must be met without sacrificing component or system life. To ensure the long lives, Lewis researchers are involved in the areas of design, life prediction, and nondestructive evaluation.

The intent of this paper is to familiarize northeastern Ohio business people with selected areas of our materials research, to indicate where the materials and design technologies now stand, to highlight some of our contributions, and to indicate areas under continued investigation.

High Temperature Materials

Figure 1 schematically shows an aircraft gas turbine engine in cross section. Incoming air (left hand side of the figure) is highly compressed and then directed to the combustor where jet fuel is added.

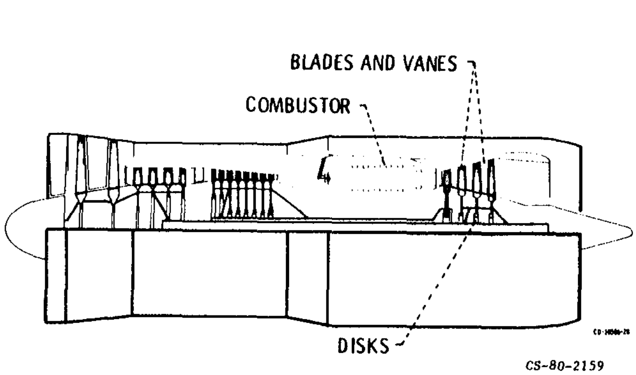


Figure 1

Flame temperatures can exceed 1500° C (~2750° F). Vanes operating at high temperature but low stress direct the hot gases against the turbine blades. The blades, in extracting power from the hot gas stream, experience the worst combination of temperature, stress, and corrosive attack in the engine. The rapidly rotating disks that hold the blades run at even higher stresses but at more moderate temperatures.

To manufacture turbine disks that will carry the high mechanical loads imposed by the rotating blades, we are developing advanced powder metallurgy techniques. One such concept involves the development of dual property disks. This approach involves a hollow metal container or can having the approximate shape of the final disk. The can is rotated and partially filled with powders of one alloy. The process is continued by completing the filling operation with powders of a second alloy. After sealing the can the powder is compacted to full density by the combined effects of temperature and pressure in a hot isostatic press. After inspection the disk is machined to final dimensions. The resultant disk consists of two alloys: one chosen for creep resistance located at the disk's rim, and the other chosen for low cycle fatigue resistance located throughout the remainder of the disk and at the bore. In this way the properties of the disk can be tailored through controlled powder compositions, resulting in improved performance. Additional benefits of the use of the powder metallurgy process are increased homogeniety of the resultant materials leading to smaller potential defects and thus longer potential lives. Materials costs are significantly decreased because the final pressed compact is close to the actual disk shape and thus requires little supplementary machining.

To improve the performance of turbine blades, which are exposed to high stress, high temperature gradients, and a corrosive environment, we are casting metal into a specially designed mold which extracts the heat only through the bottom (fig. 2). In this way solidification starts at the chill and proceeds through a tortuous path which allows only a single grain to grow. The product is a single-crystal turbine blade (ref. 1). Because grain boundaries are absent, material made this way has superior resistance to cracking caused by thermal cycling. Together with compositional changes permissable in single crystal castings, the superior thermal fatigue resistance allows the blade to be used at temperatures approximately 75° C (150° F) higher than a conventionally cast counterpart.

Turbine vanes are directly exposed to the high temperature gases leaving the combustor and thus must have high melting temperatures as well as moderate strength at high temperature. To extend the

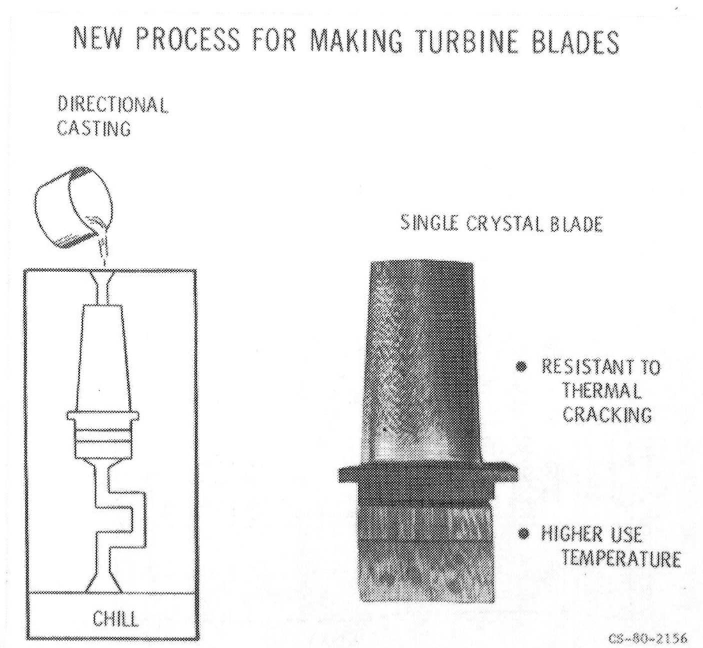


Figure 2

useful operating temperature of turbine vanes, Lewis has participated in the development of materials that are strengthened at high temperatures by the presence of very fine dispersed oxide particles (ref. 2). The first step in manufacturing an oxide dispersion-strengthened material is to mix (knead) fine oxide particles into metal alloy particles (fig. 3). To do this we use the product of one northern Ohio business, the attrition mill, which is a high-energy, rapid, stirred ball mill. (We are also using such mills to reduce the size of ceramic particles for our ceramic materials development activities.) Once milled, the powders are sealed in a metal container and extruded through a die, for example, into the shape of a vane airfoil. A superalloy that contains no oxide strengthening particles shows a rapid drop off in 100-hour rupture strength with temperature and very low strengths beyond about 900° C (1800° F). The same alloy with the finely divided oxides present, maintains a reasonable strength to temperatures approaching 1100° C (2200° F).

As an alternative to developing higher and higher use-temperature metals, we are also developing ceramic coatings that insulate the surfaces of aircooled metal components from the very high temperature combustion gases (ref. 3). Using the coating application process called plasma spraying (see fig. 4), we first deposit an oxidation resistant bond coat to the metal blade, vane, or combustor then an overcoat of zirconium oxide to which small amounts of yttrium oxide have been added to make the ceramic more resistant to thermal cycling. In the presence of high-temperature gases a layer of this zirconium oxide only 250 to 375 micrometers (0.010 to 0.015 in.) thick can lower the metal temperature of an air-cooled component by 50° to 100° C (100° to 200° F) or more. Such coatings are good reflectors of radiation and thus lower the radiant heat transfer to the components as well. In addition, the ceramics have the potential for improved resistance to high-temperature corrosion. Although figure 4 shows the coating being applied manually, Lewis is currently developing an automated system that not only will uniformly and reproducibly apply any thickness of coating to any point on the airfoil, but will also measure the coating thickness and tell itself what areas are thin and require additional coating to meet specifications.

For higher temperature applications there is considerable interest in the use of ceramic parts. Figure 5 is a schematic of an automotive gas turbine in which the ceramic combustor, power turbine,

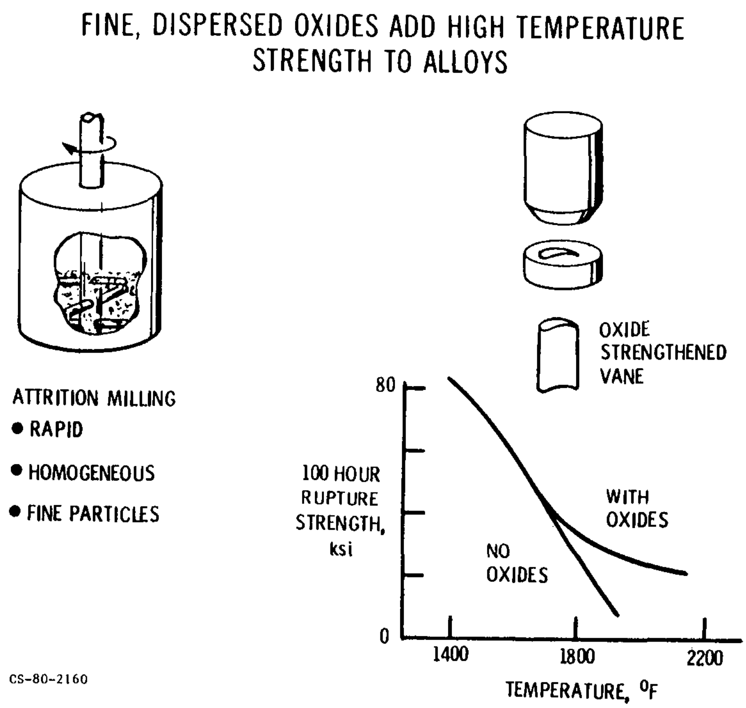


Figure 3

CERAMIC COATING PERMITS LOWER METAL TEMPERATURES

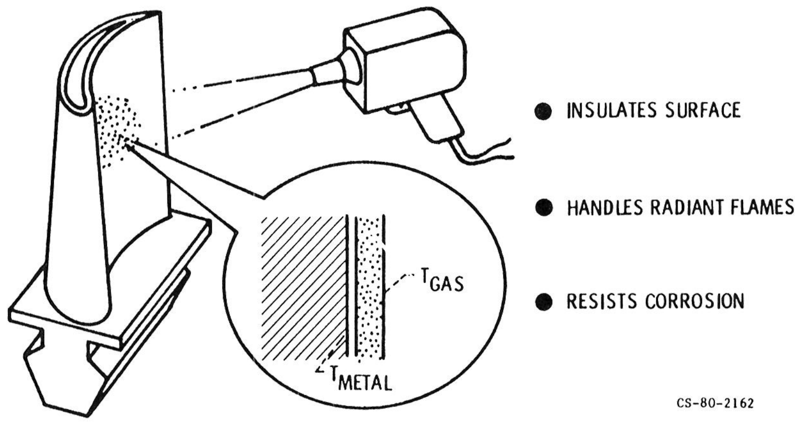


Figure 4

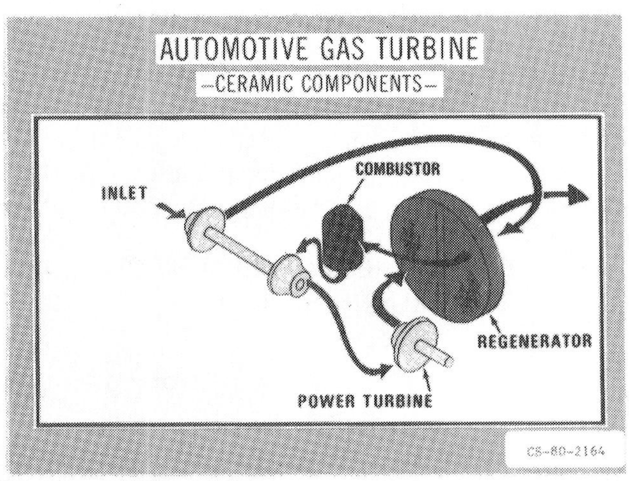


Figure 5

and regenerator are shown. For the automotive gas turbine to significantly exceed the performance capabilities of current internal combustion engines, such parts will have to operate at temperatures beyond the capability of superalloys. In addition, ceramic parts of very complex geometry must be capable of being fabricated inexpensively and in large numbers. While most of the Lewis materials effort for automotive gas turbines is described in another paper at this conference, the significant materials research and development activity here in that research area is exemplified by the development of the silicon nitride automotive turbine rotor. Here, silicon metal powder is mixed with a binder and injection molded or slip cast to a very complex shape (fig. 6). The casting is then heated in nitrogen, whereupon the silicon reacts with the nitrogen and forms silicon nitride (Si_3N_4), a high-temperature ceramic (ref. 4). There is very little dimensional change on firing, so the final part requires little or no finish machining. The use of ceramics like silicon nitride allows high temperature operation without cooling air, thus leading to significantly reduced component complexity. The low density of ceramics minimizes operating rotational stresses and total system weight. Also, such components use no strategic materials, and, if they can be developed, will help the United States minimize its dependence on foreign sources of critical elements.

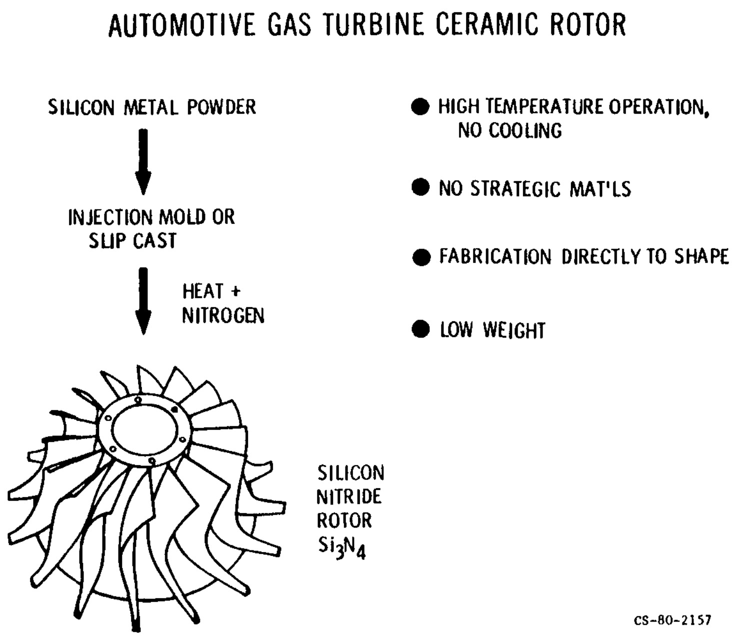


Figure 6

Composite Materials

Composite materials exist in our daily activities in many forms: from reinforced concrete, to fiber glass boats, to steel belted tires, to "graphite" skis and golf clubs. However, few of these applications reflect the full capabilities of the advanced composite materials that have been developed in the aerospace industry during the past two decades. On a pound-for-pound basis these materials are stronger and stiffer than steel. Their use permits the fabrication of high performance structures that could not be considered with conventional materials. Some examples of advanced composite material uses are shown in figure 7. Although most modern aircraft use composites for selected secondary structures (fairings, flaps, interiors, etc.), the military jet shown (AV8B Advanced Harrier) is the first high-performance plane to fly with all composite wings (29 percent of the plane's structure will be composite). The engine shown in the lower left-hand corner is the QCSEE, or Quiet, Clean, Short-Haul, Experimental Engine. QCSEE demonstrates the potential for composites in flight quality hardware. Composites comprise 33 percent (by weight) of the QCSEE structure in a variety of components. Finally, the need for more fuel efficient cars has become more apparent to all of us. The "lightweight concept vehicle" built by Ford (lower right) demonstrates a viable approach to reducing the weight of the full-size car by replacing all of the major structural components with compoosites. (In this demonstration a net decrease in weight of 560 kg (1250 lb) was attained.) All of these applications reflect activities aimed at improved performance coupled with significantly decreased weight. When fully developed, such approaches can provide better fuel efficiency or greater payload. The following review of some basic concepts of composite materials will show how Lewis is expanding the technology of composites for use in even more demanding applications. The inset in figure 8, a cross section of a fiber-reinforced composite material, indicates the basic features of a composite: a laminar array of fibers in a supporting matrix. This concept can be used in many variations, including orienting selected plies (laminae) in different directions, using woven cloth or multifiber rows rather than single fibers, etc. The desirable structural properties of composites are due primarily to the strengths (greater than 3000 megapascals (500 000 psi)) and stiffnesses (greater than 300 000 megapascals (50 million psi)) of the high performance fibers now available. These factors are most evident in modern graphite fiber composites that combine the remarkable properties

APPLICATIONS OF ADVANCED COMPOSITES

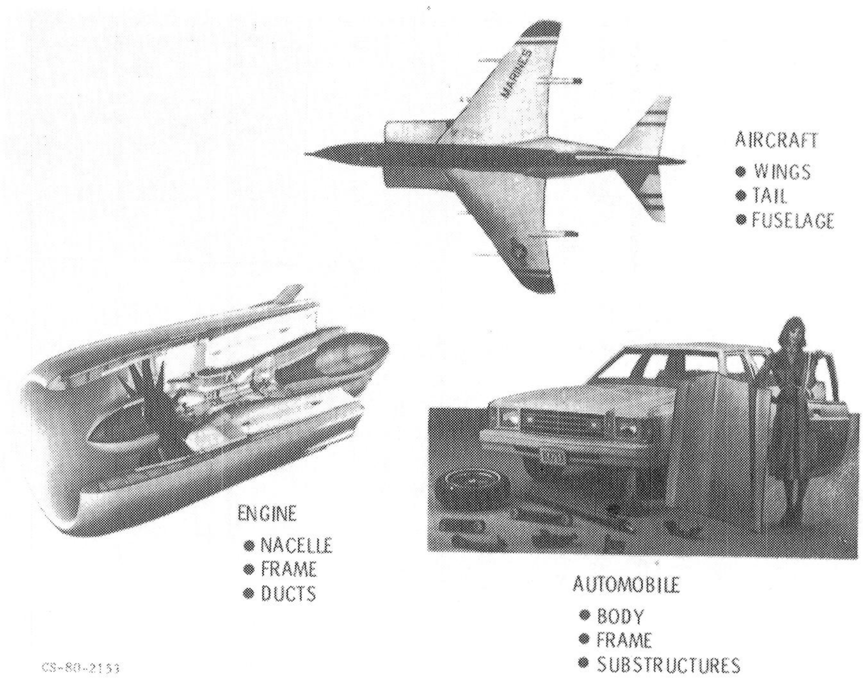
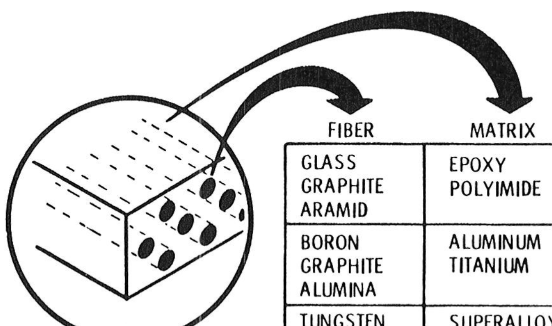


Figure 7

MATERIALS FOR ADVANCED COMPOSITES



FIBER	MATRIX	APPROXIMATE TEMP. CAPABILITY, °F
GLASS GRAPHITE ARAMID	EPOXY POLYIMIDE	300 600
BORON GRAPHITE ALUMINA	ALUMINUM TITANIUM	600 1000
TUNGSTEN GRAPHITE SILICON CARBIDE	SUPERALLOYS GLASS/CERAMIC CARBON	~2500 ~3000 >3000

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Figure 8

of very low density graphite fibers with organic or metallic matrices. Most of the applications shown in figure 7 are graphite fiber epoxy matrix composites.

Polymeric matrix materials have been predominantly employed because of their low density and convenient processability. A wide variety of polymers are used. The first two examples shown (epoxy and polyimide) reflect the use temperatures of interest in aerospace applications. The emphasis on propulsion systems at Lewis has led to the investigation of several such composite systems for applications in the 300° C (600° F) range and beyond. Graphite/polyimide composites have received

major emphasis among the polymer systems; boron/aluminum is a prime contender for lightweight intermediate temperature applications among the metal matrix materials; and tungsten/superalloy composites are being investigated for high strength, high temperature turbine applications. Thus, composites can be tailored to the needs of most applications on the basis of strength and stiffness as well as on the basis of use temperature.

Figure 9 lists some of the major benefits that can be derived from composite materials. Foremost are high strength and/or high stiffness at relatively low weight compared with conventional materials. The bar charts at the right show properties for two composite systems and for steel and aluminum. The fourfold advantage of unidirectional graphite/epoxy over these metals is clear. As noted, these properties can be tailored to the needs of specific structures by orienting fibers in the direction requiring strength or stiffness. Also, many composites offer improved corrosion resistance when compared with conventional materials and, as in the commercial plastics industry, many composite designs offer one-step processing of complex structures having integral stiffeners, fasteners, etc. This aspect (as well as other material and processing factors) can provide lower production costs for the composite component.

Research at Lewis has focused primarily on the polymer matrix composite systems of high temperature capability. The development of a high-temperature matrix resin designated PMR-polyimide (refs. 5 and 6) led directly from that research. This polymer, now commercially available, has been very successfully fabricated into low void, complex-shape composite structures for use at temperatures to 300° C (600° F). Figure 10 shows how PMR composites are produced. Graphite fibers are passed through a monomer solution (melt impregnation is also used). Polymerization is carried out on the fiber (in situ); individual plies are cut and stacked in selected orientations. These plies are then pressed in a die near 300° C (600° F) into airfoil shapes. The PMR system has demonstrated improved performance in the production of flight quality hardware and improved processability, both of which promise reduced production costs for appropriate applications.

The PMR polyimide matrix resin is being used in many applications that benefit from the lightweight high strength aspects of graphite/polyimide composites and require operation near 300° C (600° F). Figure 11 shows some typical applications of the PMR polyimide system. Major applications are on aircraft engines. The development of the graphite/polyimide duct for the QCSEE engine (fig. 7) provided the technology base for the production of a large outer duct for the Navy fighter engine shown here. Beyond the significant weight saving is a substantial cost saving based on the difference in the projected fabrication costs of the PMR duct and the original titanium duct. A

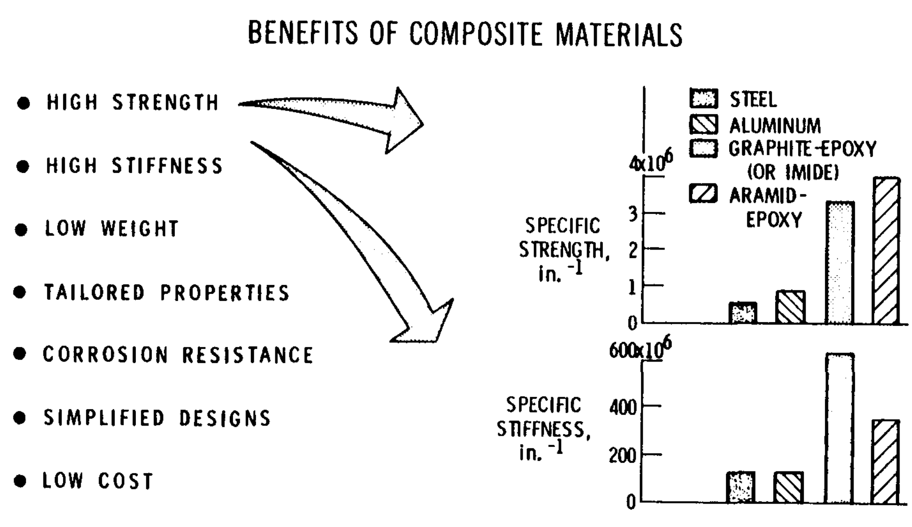

Figure 9

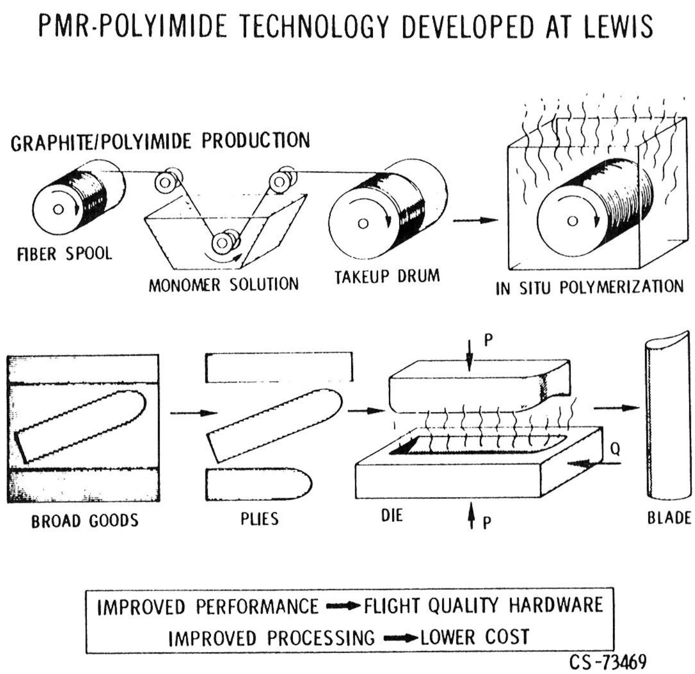

Figure 10

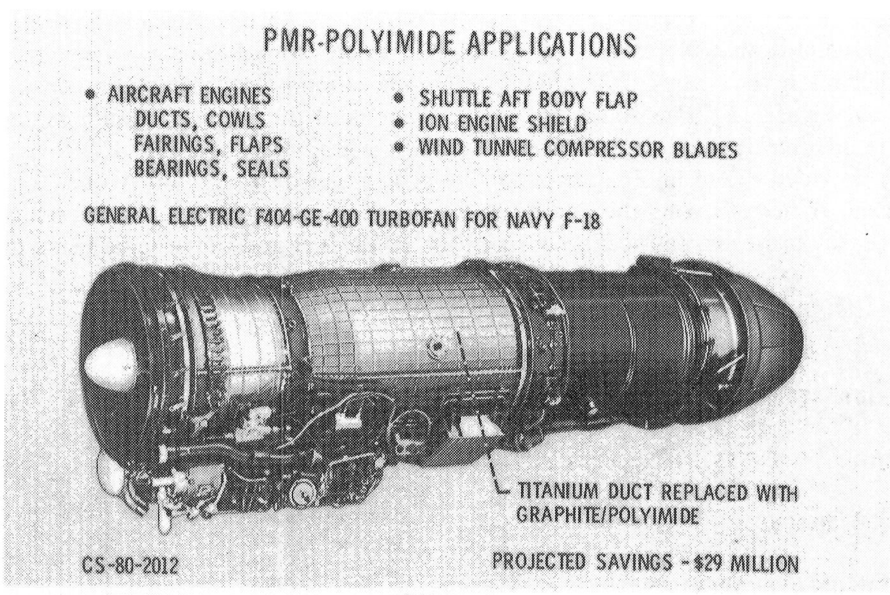

Figure 11

variety of other engine components have been produced or are being considered for production. Potential spacecraft applications have been demonstrated for the NASA Space Shuttle and for ion engine hardware. In another aspect of aeronautics research, an extensive set of large compressor blades has been fabricated for use in a major wind tunnel facility.

NASA is also concerned about limitations in polymer matrix composites. Because these materials are flammable, methods are being developed to minimize the flammability of the polymers and to

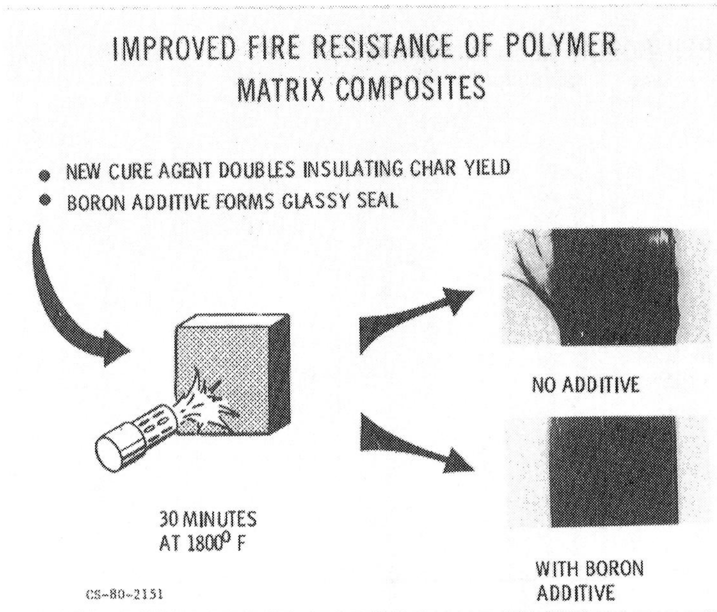

Figure 12

minimize the loss of matrix and fibers in a fire situation. Two examples of this work are shown in figure 12. In one approach, a new cure agent doubles the insulative char formed when a conventional aerospace epoxy composite is exposed to a fire. Thus a minimal change in current materials and processes produces a significant improvement in fire resistance. A second approach involves the addition of boron powder to the matrix material. The boron forms a glassy surface layer during exposure to fire, thereby minimizing the loss of material and maintaining structural integrity even under conditions (30 min at 1000° C (1800° F)) simulating a jet fuel fire.

The applications discussed above represent low or moderate temperature areas of aircraft engines. The applications are varied (besides those noted in figure 11, there are fan containment systems, sound suppression systems, compressor vanes, engine nacelles, and more), but they do not address several major engine components. Significant gains in engine performance can be made by using lightweight high performance materials in rotating components such as fan, compressors, and turbines, and, as mentioned earlier, increasing the turbine operating temperatures is desirable as well. These are all very challenging materials problems, but composite materials are being evaluated which show exceptional promise for such applications.

The requirements for rotating components are particularly stringent because such components must survive the high-velocity impact of runway debris, ice, birds, etc., which may be injested into the engine (primarily during takeoff and landing). At Lewis substantial gains have been made in the production of improved lightweight boron/aluminum composites for impact tolerant structures (refs. 7 and 8). Figure 13 shows a bar chart of impact strengths for notched, unidirectional, composite specimens (made using early fabrication technology (c. 1974)), for titanium alloy specimens, typically used for fan blades, and for an improved composite incorporating large-diameter boron fibers, a more ductile aluminum matrix, and a more carefully controlled production process. Note the fourfold increase in impact strength for this optimized materials system. Although composite fan blades (as shown at the right in this figure) have been fabricated, further design and process development is needed to achieve the required impact properties in these more complex structures.

Finally, another area of advanced, high temperature composite materials development involves the fabrication and evaluation of fiber-reinforced superalloys for very high temperature applications (ref. 9). Composite materials offer significant advantages for such high temperature components because they exhibit exceptional strength at temperatures well beyond the capability of conventional

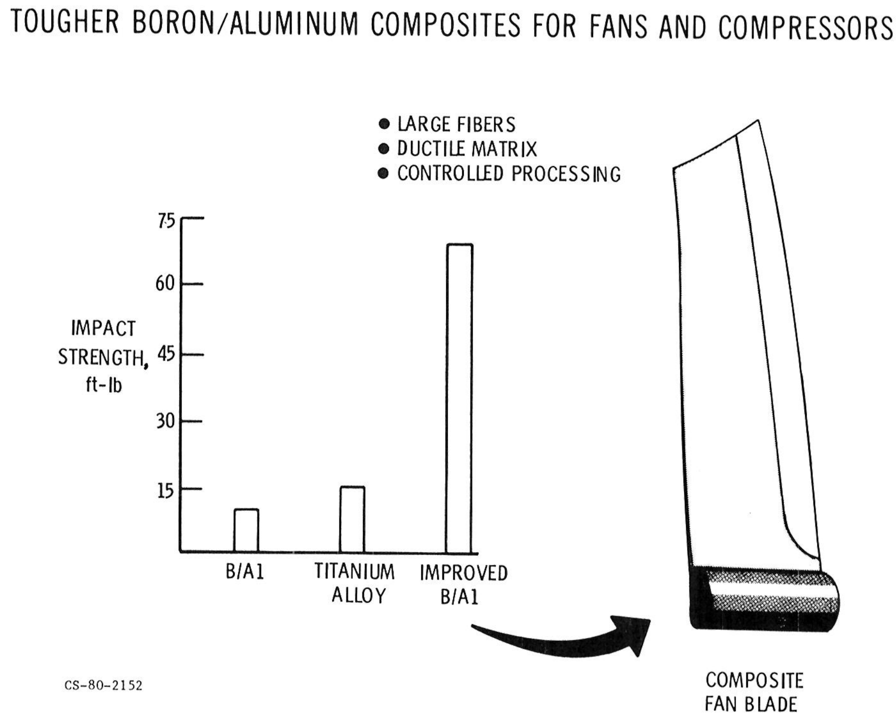

Figure 13

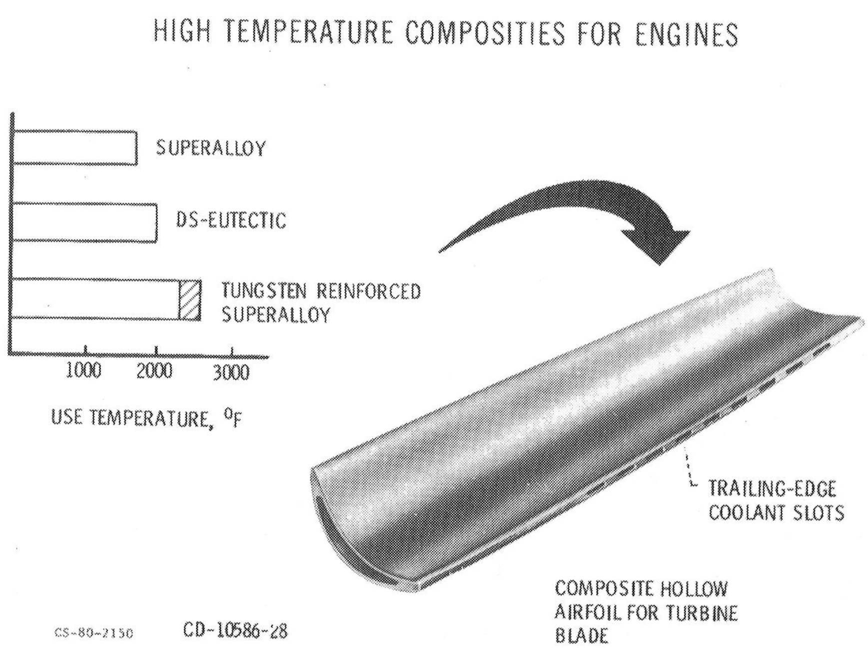

Figure 14

superalloy materials. The bar chart in figure 14 compares the use temperature of a conventional superalloy (1000° C or 1800° F), a directionally solidified eutetic (1100° C or 2000° F), and a tungsten-fiber-reinforced superalloy composite (1200° C or 2200° F for a current superalloy matrix). The shaded area indicates the potential for increased temperature using advanced superalloy

matrices. The photograph at the right shows a hollow airfoil shape which was successfully fabricated from tungsten wire reinforced superalloys.

Composite applications are rapidly expanding in aerospace hardware in a vast array of general purpose items. Advanced composite materials offer some exceptional benefits and, as material and processing costs continue to be reduced, these materials will find their way into a wider variety of commerical products.

Advanced Design and Life Prediction

As better materials come into use, they are often pushed to the limits of their capabilities. Any material used severely enough will, of course, fail. For example, the older bridges in the Cleveland area, like turbine engine parts, follow a failure curve such as shown in idealized terms in figure 15.

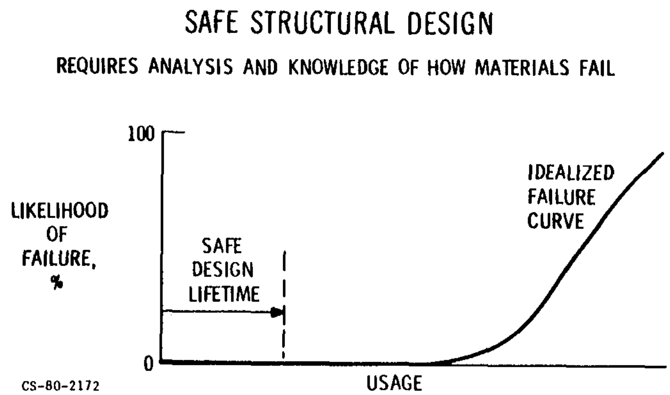

Figure 15

The likelihood of failure increases as the usage increases. In order to avoid unexpected failures, we must be able to accurately calculate a safe structural design lifetime in advance of service. This ability requires several important ingredients. One of the most important ingredients is the ability to analyze and calculate the magnitude of the stress and strain at the most critical location in a component part, since it is the critical local condition that is the origin of failure. Mechanical failures occur either because the stresses and strains are too high, or because the part has a region of unintentionally low weakness. The process of assessing structural lifetime in advance of service, called design by analysis, is graphically described in figure 16. This approach is mandatory for expensive, complex, long lead-time structures for which the old concept of "build 'em and bust 'em" is an impossibility. By combining a model of the component geometry with the material's properties and the anticipated use conditions and by adding a little past experience, one can conduct a structural analysis for the local stresses and strains that will indicate the potential material failure modes. And, based on those modes, one can then calculate a safe design lifetime.

In the area of structural analysis Lewis is both a user and a developer of finite-element computer programs. Two such programs are shown in figure 17. The MARC program is used at Lewis for the analysis of high temperature thermal fatigue problems (refs. 10 and 11). In MARC small, finite elements, or building blocks, are used to represent the turbine blade of interest, rather than treating such a blade as a continuum that would require an infinite number of locations of stress and strain to be calculated. The program calculates the stress and strain on each of these building blocks in terms of the applied mechanical and thermal loads. NASTRAN (ref. 12) is the NASA-developed finite-element computer program which is used for either small or large structures. In NASTRAN the building blocks can take on the appearance of the actual structural members. NASTRAN was used to

DESIGN BY ANALYSIS

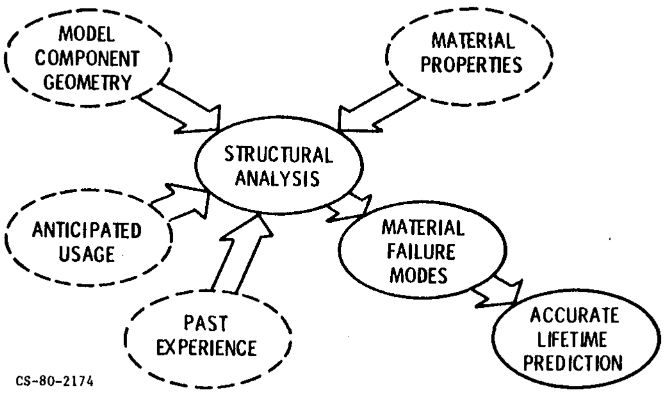

Figure 16

FINITE ELEMENT COMPUTER PROGRAMS

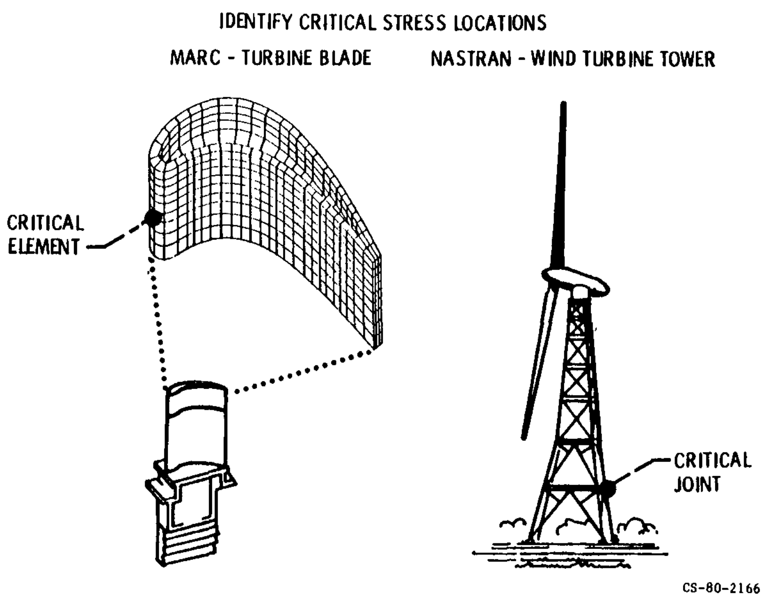

Figure 17

calculate the loads carried by a wind turbine tower (ref. 13) at each structural joint. The crucial joint, that is, the one carrying the greatest load was thus located. NASTRAN has, of course, been used in countless other applications over the years including the designing of composite structures, automotive bodies, etc.

Now let us examine, briefly, how materials fail in gas turbine engines. Fatigue crack initiation, propagation, and ultimate fracture result from the application of cyclic stress and strain. Fatigue cracks initiate at localized microscopic inhomogeneities in the material. Continued cycling causes the crack to grow and propagate deeper and deeper until a critical length is reached and catastrophic fracture suddenly occurs. Creep rupture is a high temperature failure mode. Creep rupture occurs when a substantial load is applied to a material. Thermally activated diffusion mechansims cause the

material to stretch; that is, it creeps, until it thins down or cracks to the point where it can no longer carry the applied load. A rapidly rotating turbine blade, for example, is subjected to creep due to the high centrifugal loads at high engine operating temperatures. Environmental attack is also a serious failure mode at high temperatures. Here, the elements in the gas turbine environment combine chemically with the metallic surface to form undesirable products. This depletes the material of strengthening elements, and, because the cross-sectional dimensions are decreased as the depth of attack proceeds, the available load-bearing area can be substantially reduced. Finally, we get to a prevalent failure mode in gas turbine engines, and one which is highly complicated because it comes about as a consequence of the simultaneous action of fatigue, creep, and environmental attack. This combination of attack modes is called thermal fatigue. The cyclic action, which is associated with the fatigue contribution, is imposed by the start-stop, heat-up–cool-down operation of an engine. The differential expansion produced by temperature gradients within a material causes self-imposed cyclic stresses and strains. Thermal fatigue cracking or heat crazing is also encountered in such diverse situations as high temperature forging dies, and automotive exhaust valves.

Once we know how materials fail, we must then become quantitative and calculate how long it will take before failure occurs. Each of the failure modes described in the previous figure has been addressed by Lewis engineers, and numerous life-prediction methods have been developed. A rather simple but highly useful method, called the method of universal slopes, has been developed at Lewis (ref. 14) to estimate material fatigue crack initiation resistance. This method can be used without having to conduct a single fatigue test. The required input comes from the properties measured in a tensile test. The required properties are the ductility, D (based on reduction of area), which governs low cycle fatigue resistance in the range from 1 to about 1000 cycles to failure, and the ultimate tensile strength, σ_u, and the modulus of elasticity, E, which govern the life, N_f, in the 1000 to 1 million cycles to failure range. The equation of universal slopes relates the cyclic total strain range, $\Delta\epsilon$, to the fatigue life, N_f, as shown,

$$\Delta\epsilon = 3.5\, E^{\sigma_u} N_f^{\,-0.12} + D^{0.6} N_f^{\,-0.6}$$

The chief advantage of the method is its low cost, and, in fact, handbook values of tensile properties can be used to estimate fatigue properties in the early stages of design. The accuracy is approximately plus or minus a factor of five in life. This is usually considered acceptable considering the large degree of scatter associated with the inhomogeneous fatigue process.

Lewis engineers have also made important contributions in the area of describing and predicting the lifetime of materials containing fatigue cracks or flaws, that is, the time the material can be used before catastrophic failure results. This area is called fracture mechanics. At Lewis we have derived accurate equations (refs. 15 to 17) for the stress field surrounding the tips of cracks in loaded structures. We have also contributed to the development of new calculational techniques (ref. 18). The quantity used to describe the stress field around a crack is called the stress intensity factor, K_I, which is used to relate the applied load, crack length, and other geometric factors that contribute to the crack tip stresses. We have applied fracture mechanics concepts to predict the rate of cyclic crack propagation in aerospace structural components (ref. 19). The primary purpose is to calculate the remaining safe lifetime available to any part before it must be removed from service. Finally, Lewis, in conjunction with other research organizations and the American Society for Testing and Materials, has contributed significantly toward the development of standardized tests (ref. 20) for measuring the fracture toughness K_{Ic} of cracked materials.

Several approaches have been developed at Lewis for predicting the lifetime of materials used at high operating temperatures. An example of these is the time-temperature computer program called MEGA (ref. 21). MEGA is the most recent of a long line of time-temperature–creep-rupture parameters that we and others have developed. MEGA enables us to estimate creep-rupture life in the long-time region from data collected in more affordable, short tests. The method has been verified to be accurate within a factor of two in lifetime for extrapolations as much as 10 times the greatest life

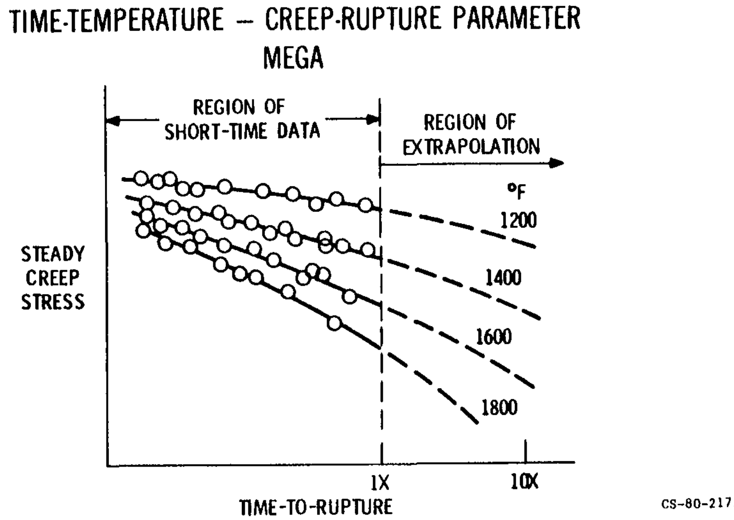

Figure 18

for which data exist (fig. 18). MEGA, therefore, permits a tradeoff between testing at a low temperature for very long times and testing at a higher temperature for much shorter times. The basic advantage of using MEGA is the cost saving accrued by not having to conduct long and expensive creep-rupture tests. MEGA is the most accurate of any such parameters available today.

We have also developed a new computerized approach for estimating the degree of environmental attack due to hot corrosion and oxidation. This method is called COREST (for corrosion estimation (ref. 22)). Based on measured weight change data, values of attack can be calculated which are accurate to within a factor of 3 in depth over the range from 0.04 to 40 mils (1 to 1000 micrometers). Typical results are shown in figure 19. Efforts are continuing to further improve the accuracy of this life prediction method. The advantage of the approach is similar to that associated with MEGA: cost saving due to the elimination of long-time testing.

Figure 20 reflects on the fact that thermal fatigue is an interaction of fatigue, creep, and environmental attack, thus making it a complex failure mode. Thermal fatigue life-prediction methods have been developed at Lewis ranging from approximate to sophisticated. An approximate

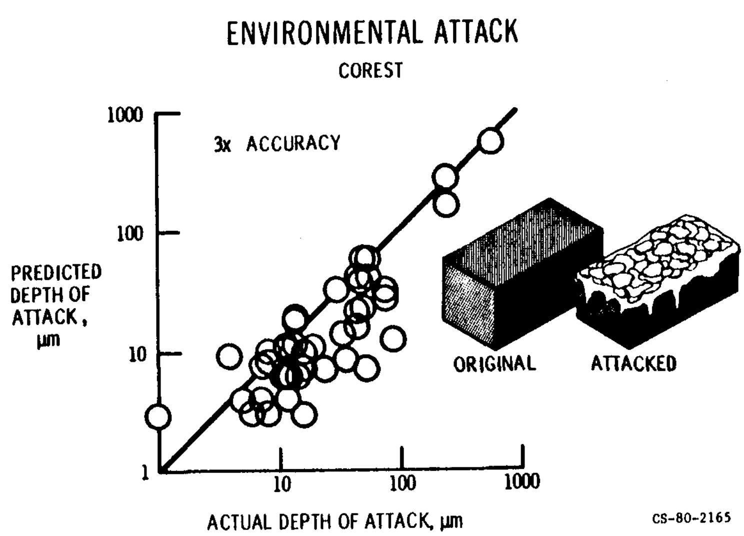

Figure 19

THERMAL FATIGUE
IS AN INTERACTION OF INDIVIDUAL FAILURE MODES

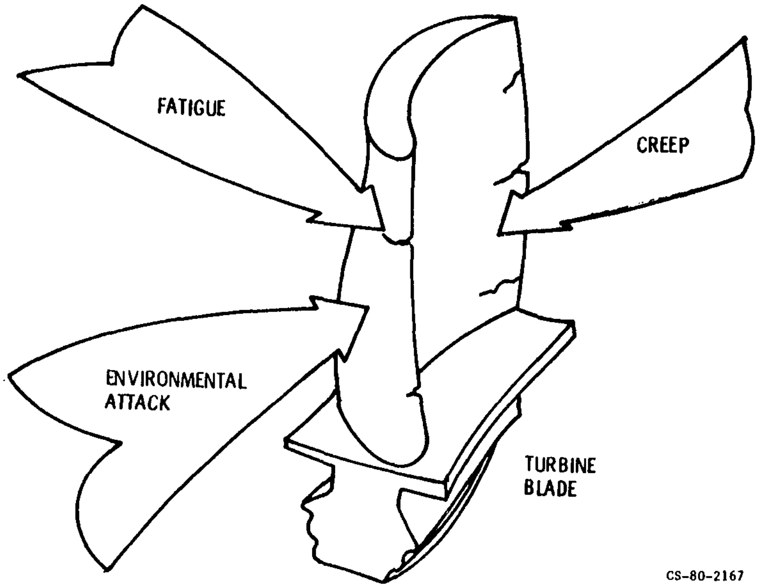

Figure 20

method, called the 10-percent rule (ref. 23), is the simplest to apply but, of course, is the least accurate. It is based directly on the method of universal slopes, discussed earlier and requires only high temperature tensile properties as input. The basic idea behind this rule is that the effects of creep and environmental interaction tend to initiate fatigue cracks much earlier than would normally be required, thus leaving only about 10 percent of the total fatigue life that one would otherwise expect. At the intermediate level of complexity is the time-cycle fractions method (ref. 24). Its application requires a knowledge of a material's fatigue and creep-rupture curves. Both of these types of curves can be estimated by methods previously discussed. This approach is more accurate than the 10-percent rule, that is, a factor of ±5 on life. A version of this method has been adopted by the ASME Boiler and Pressure Vessel Committee for use in Code Case 1592 for high temperature pressure vessels and piping components (ref. 25). Finally, we have developed a sophisticated method called strainrange partitioning (ref. 26) which permits the most accurate predictions of thermal fatigue life available to date. The accuracy is offset by the fact that specialized laboratory specimen data are required to achieve the ±2 accuracy. Some techniques for estimating the strainrange partitioning characteristics of a material from a knowledge of tensile and creep-rupture ductility data are, however, under development (ref. 27).

Nondestructive Evaluation

Nondestructive techniques have for years been used to inspect components for cracks, inclusions, and variations in thickness as depicted in figure 21 (ref. 28). Crack inspection has involved such approaches as dye and liquid penetrants, eddy current, and ultrasonics. Inspection for inclusions has primarily been conducted by using X-ray techniques. Thickness variations have been measured by gage blocks, micrometers, and, more recently, a variety of laser and other optical approaches. Such techniques are applicable not only to the raw material prior to manufacture, but also to finished parts and parts that have been in service and require inspection to determine fitness for continued use. As we design components for high performance, we press the usage of materials to their limits. Thus, we

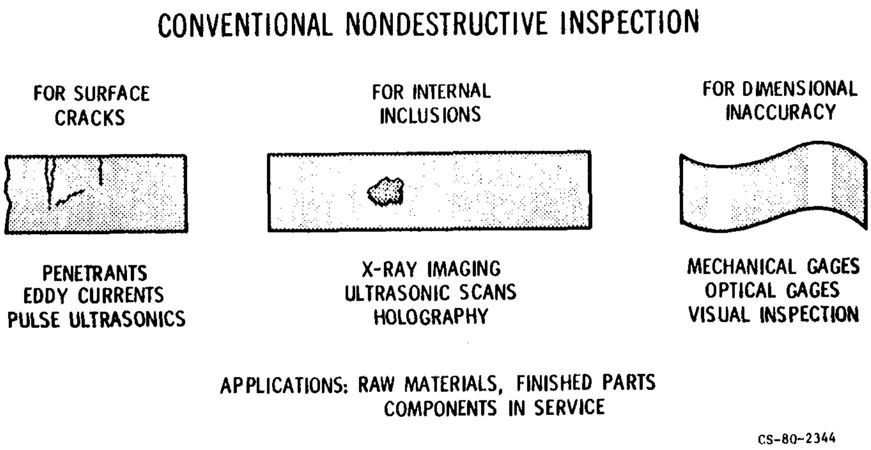

Figure 21

are no longer concerned with only cracks, inclusions, and variations in thickness, but with the variations in the mechanical properties of the specific materials and components as well. It is quite possible for raw materials and finished parts to have no conventional defects and yet still not be safe. They may have areas of low strength or other poor mechanical properties. Properties that could cause early component failure also include lower fracture toughness in metals, or lower interlaminar shear strength for composites. To conduct destructive tests on all material to be used is expensive, and we obviously cannot destroy a part to find its strength. For these reasons the Lewis focus in nondestructive evaluation is on the determination of specific physical properties, or variations in such properties, within a material or finished part. The concern here is exemplified by the situation depicted schematically in figure 22.

As discussed above, the likelihood of failure is related to usage for the ideal situation. However, in the case of defective or "off-specification" materials, the likelihood of failure increases more rapidly

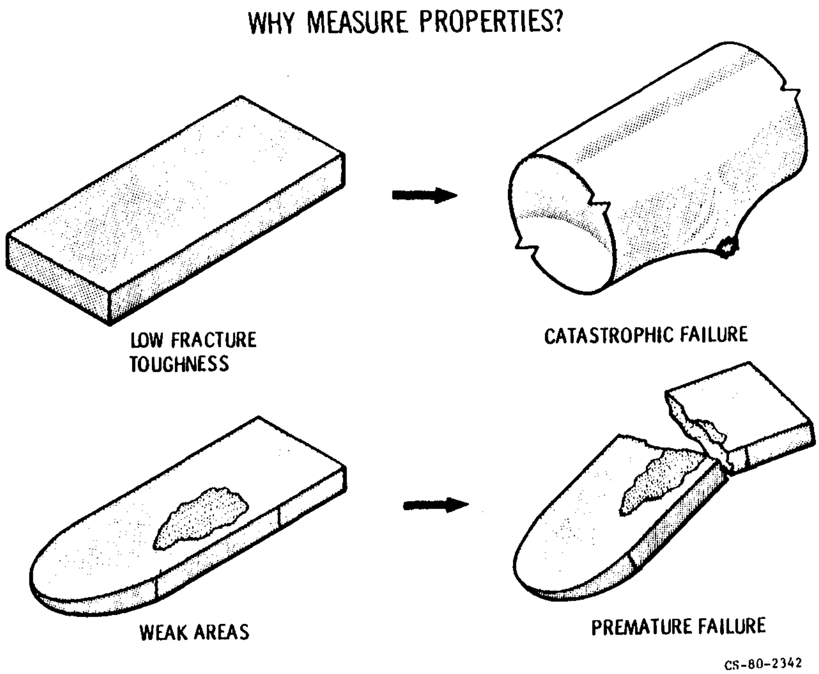

Figure 22

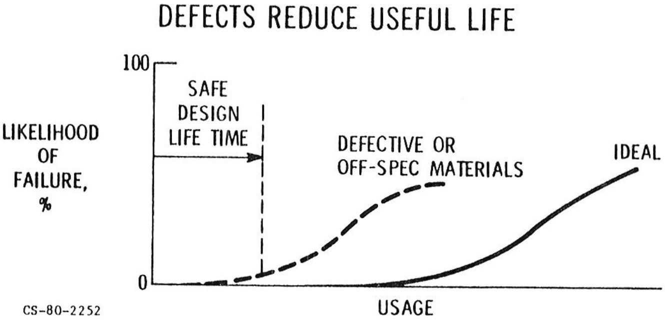

Figure 23

with usage, and safe design lifetimes based on ideal or homogeneous properties are optimistic. Thus, an unexpected early component failure may well result as shown in figure 23. At Lewis we have developed advanced ultrasonic methods with which to evaluate those material variables that govern critical properties. These methods are based on the fact that the microstructure of a material (i.e., the grain size, composite fiber fraction, void content, amount of precipitate present, and other characteristics) controls the way in which materials fail (refs. 29 to 33). As shown in figure 24, these same microstructural factors control the way an ultrasonic wave passes through a material. Thus, by analysis of the changes in ultrasonic waves passing through a material, it is possible to relate a nondestructive quantity to the destructively measured properties. Such an analysis of the ultrasonic waves passing through materials is performed by computer using mathematical equations to derive the quantities required to correlate wave behavior with material properties. Figures 25 to 27 show the laboratory procedure for establishing such correlations (refs. 34 to 37). First, an ultrasonic wave is captured and digitized. The wave is then analyzed to determine what the material microstructure did to the signal. Second, as shown in the left plot of figure 26, mathematical curve fitting establishes the filtering effect the material has on the ultrasonic wave. Such information is used to plot the attenuation of the ultrasonic waves as a function of frequency, as shown in the plot on the right side of the figure. The slope of a straight line fitted to the attenuation curve gives an ultrasonic factor used to predict fracture toughness. For each individual material microstructure, an individual ultrasonic factor is established. By then destructively testing the same specimens on which the varying ultrasonic factors have been identified, a correlation factor, as shown in figure 27, can be established between

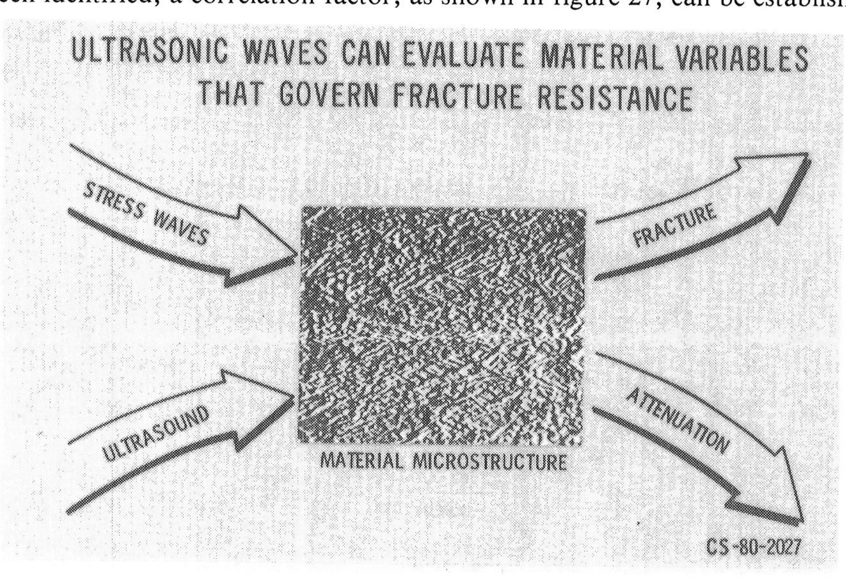

Figure 24

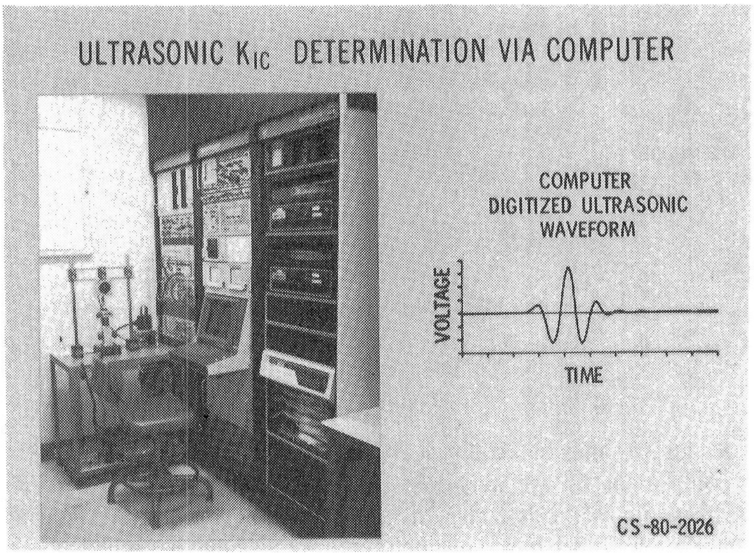

Figure 25

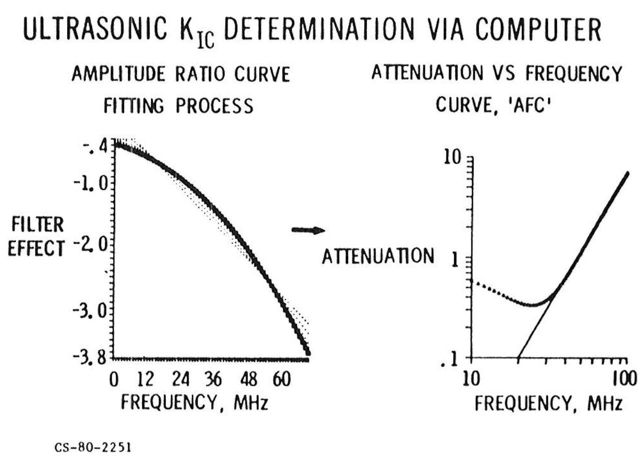

Figure 26

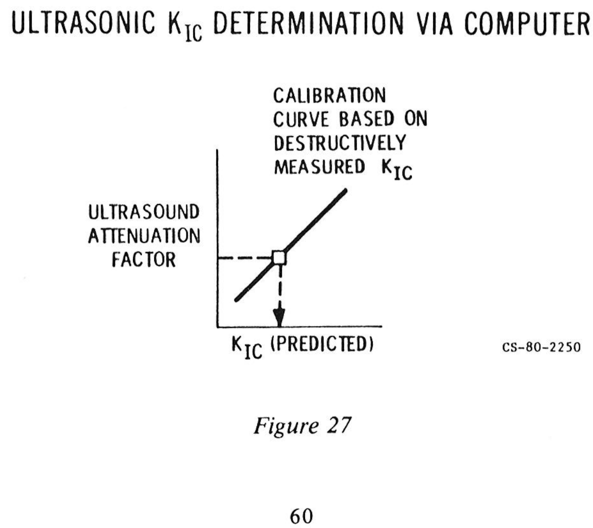

Figure 27

CORRELATION OF ULTRASONIC FACTORS AND CRITICAL STRENGTH PROPERTIES

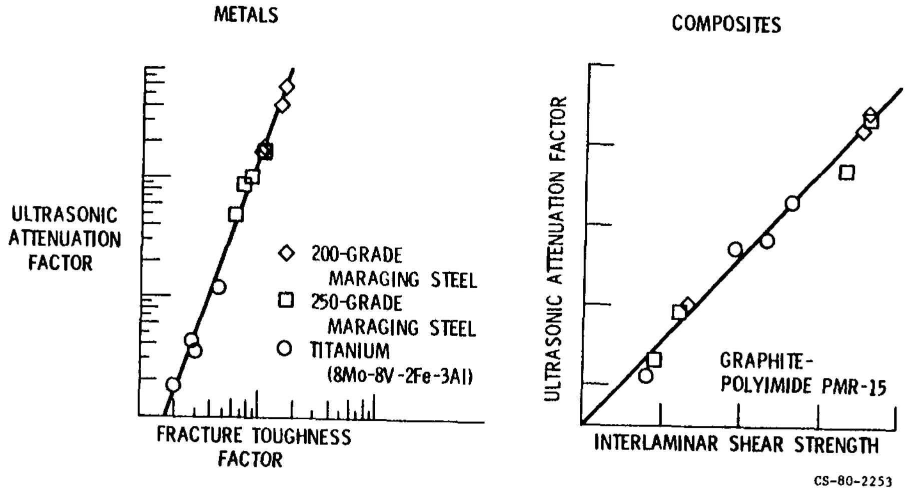

Figure 28

ultrasonic attenuation and the mechanical property of interest. In figure 28 typical correlation plots of ultrasonic factors and critical mechanical properties are shown. On the left ultrasonic attenuation factors are plotted versus fracture toughness. The log-log plots show a linear correlation between these two factors for several grades of maraging steel and for a titanium alloy having aerospace applicability. On the right, interlaminar shear strength versus ultrasonic attenuation is also plotted for graphite/polyimide PMR-15 composites (refs. 38 and 39). Note the linear correlation in this case as well.

The property determination procedure for composites is a derivation of the procedure used for metals. Because of the very heterogeneous nature of composites, an ultrasonic input is used, and the modified signal is received by an acoustic emission transducer (ref. 40). The signal is then analyzed for frequency and energy content. These data are then mathematically transformed into an ultrasonic factor which again can be plotted against the destructively determined mechanical property. The results achieved in figure 28 have been accomplished using a research laboratory facility. In addition to the research described, we are in the process of developing a hard-wired field evaluation device (fig. 29) for determining a specific critical property of a composite in place on an actual aircraft. Such an instrument is needed to monitor the residual properties of the ever increasing number of composites being used in military and commercial aircraft. This field unit will weigh about 15 pounds and will make a single measurement of the response of a composite structure to ultrasonics. The resulting number on a digital display will reflect the effect of the composite microstructure on the ultrasonic wave. This number will have been calibrated against previously destructively determined properties. Thus, the meter can be used to measure degradation of the part as well as the extent of any damage that it has sustained. A laboratory mockup of the portable system was used to map shipping damage that occurred to a Navy S3 aircraft composite spoiler. This technique more accurately mapped the damage than any other existing ultrasonic flaw detection equipment and established the repair feasibility of this costly part. We expect delivery of the first of these field instruments in the next month or so, and verification of instrument accuracy and total capability will be carried out thereafter. If this instrument continues to meet expectations, it is possible that commercial versions of this device will be available in the next year.

FIELD EVALUATION OF COMPOSITES

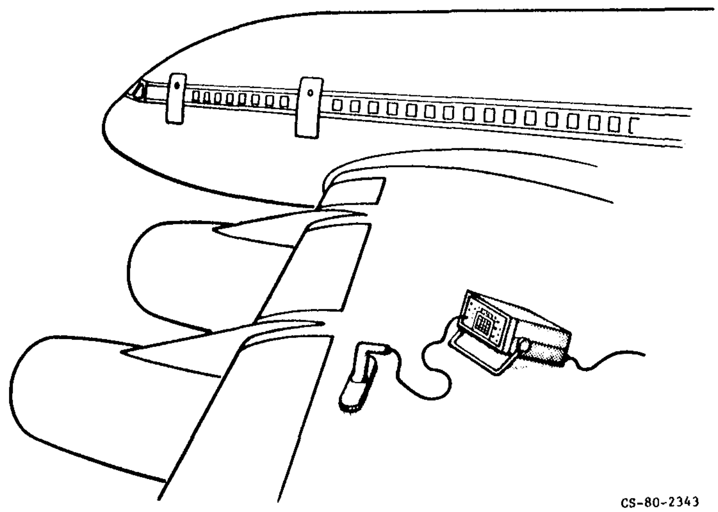

Figure 29

Concluding Remarks

This brief summary of advanced technology being developed by Lewis in four areas of materials and structural design reflects only a portion of the total effort in these areas. Figure 30 highlights items from each area presented. Single-crystal airfoils increase use temperature and are more resistant to thermal fatigue cracking. Composites allow properties of a component to be tailored to best meet the intended application. New life prediction capabilities as well as advanced design tools have been developed. And, in the area of nondestructive evaluation, our technology has extended beyond the identification of flaws and into the area of determining local materials properties with

ADVANCED MATERIALS AND DESIGN

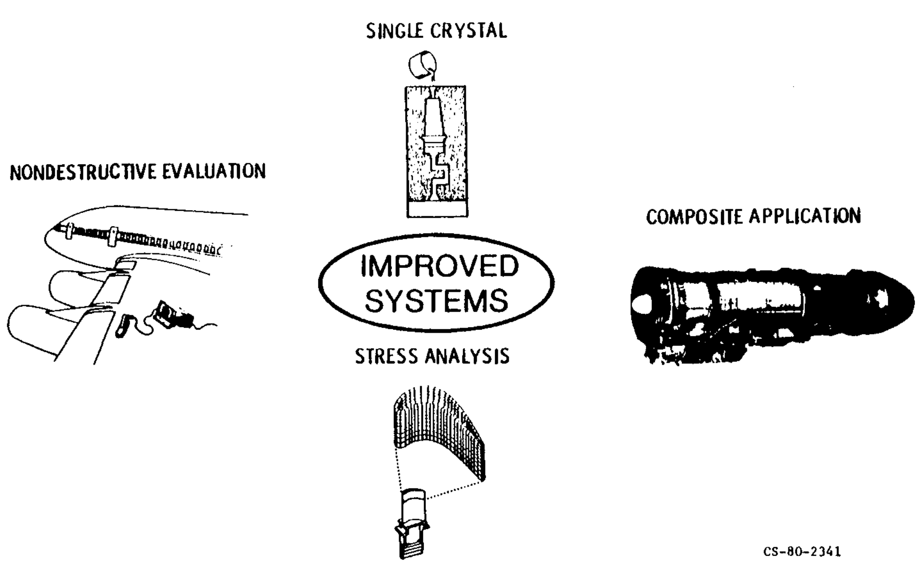

Figure 30

ultrasonic devices. As new ideas, technologies, materials, and analytical approaches are developed, they will be in NASA technology utilization Tech Briefs.

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